

An FM Crystal Set

Updated 2010-11-28:

Since this page was first posted in June 2010, I have made a number of improvements to the receiver described below. I've also received a few requests for additional information. In reviewing this page, I realized that it was long overdue for an update. The original information is unchanged. The updated information appears at the bottom of the page.

Introduction

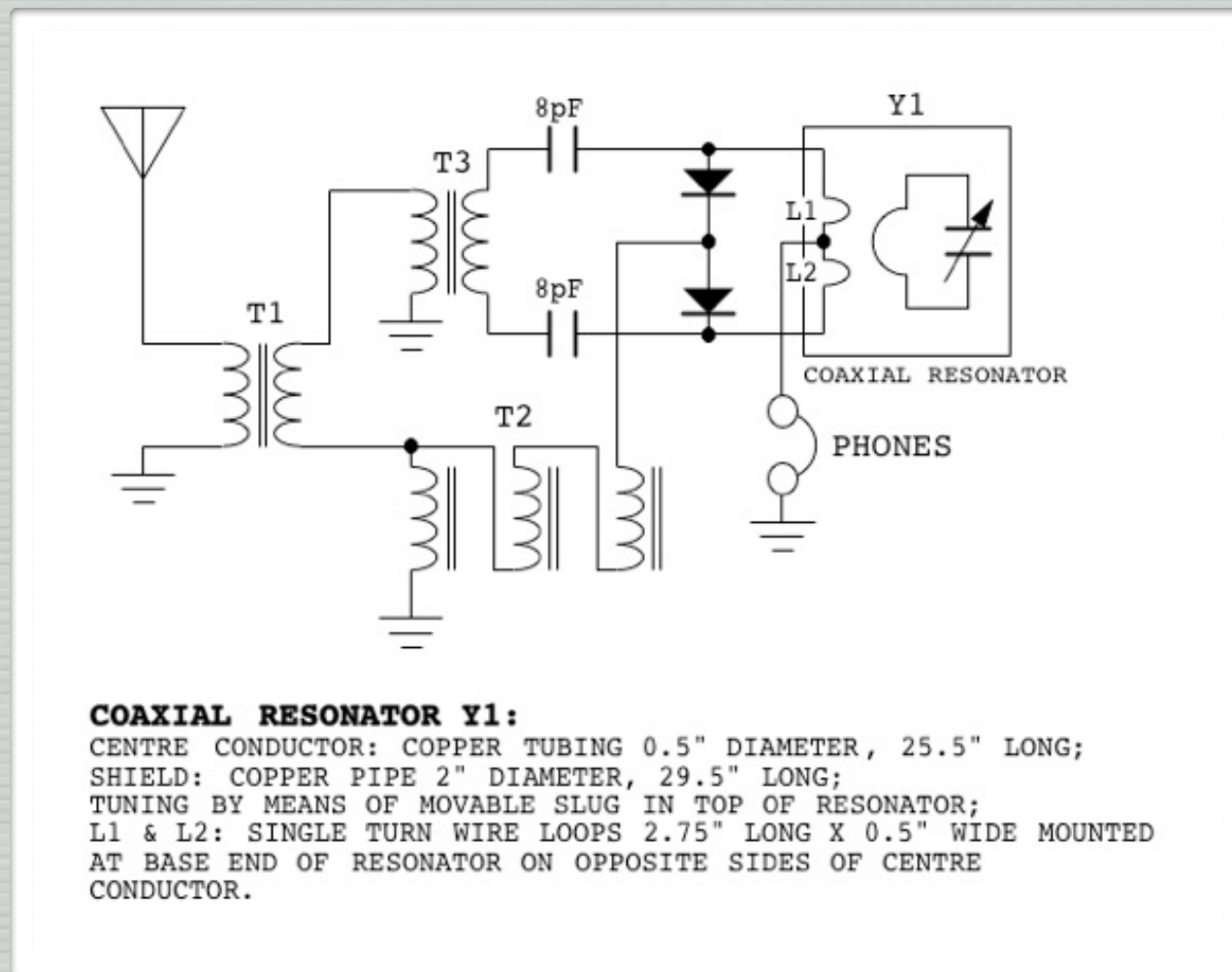
Crystal sets—totally passive receivers without any amplification—have been popular for many years. The vast majority of them are designed and built for the Medium Wave band, 530 to 1700 kHz. However, there have also been some built for the shortwave bands, and occasionally some for the FM band (88 to 108 MHz).

Having several local powerful FM stations, I'd occasionally noticed that I was picking up FM on a medium wave crystal set. Considering that there was a strong enough signal to receive FM when it wasn't wanted, it should be possible to build a receiver to pick up the signal intentionally.

Most FM crystal sets use slope detection. That is, they are tuned slightly off the centre frequency of the station, and as the frequency modulated carrier moves in and out of the receiver's resonant frequency, an audio signal approximating the original modulation is produced. True FM detection requires a frequency discriminator circuit, and the complexity generally makes it unsuitable for a passive receiver. I'm only aware of one such project. It was designed and built by Edward Richley, and was written up in the [Xtal Set Society Newsletter, January and March 1996](#). In order to achieve the high Q required, the circuit used a coaxial resonator constructed from 2 inch copper pipe. It was ingenious in that, while most FM discriminators have two tuned circuits, this one only required a single tuned

circuit. This was an important feature, because trying to adjust two tuned circuits when tuning to different stations, would be extremely difficult, if not impossible.

I've redrawn the Richley circuit here:



A very brief description of the circuit follows. For a more thorough discussion, please refer to the original newsletter articles.

As described in the diagram notes, the resonator is constructed from a two foot piece of 2 inch diameter copper pipe, with a centre conductor of 1/2 inch copper pipe. The resonator is designed for an unloaded Q of 2000, and a loaded Q of about 500, which is required for acceptable selectivity. FM channel bandwidth is 200 kHz, or 0.2 MHz. Therefore, at a frequency of 100 MHz, required Q will be $100/0.2=500$.

Transformers T1, T2, and T3 are made from standard 300:75 ohm baluns which are included in the kit of parts that come with virtually every new

television or radio. T1 is used unmodified. T2 is rewound as 1:3 autotransformer. T3 has a two turn primary and a two turn secondary. Transformer T1 converts the incoming unbalanced signal to a balanced signal which then feeds T2 and T3. The secondary of T3 is loosely coupled via the 8 pF capacitors to the resonator coupling loops, which develop a 90° phase shifted signal due to the normal behaviour of a coupled circuit at resonance. The secondary of T2 is connected to the common point between the diodes. This signal is 180° out of phase with the incoming RF. Hence, there are quadrature signals applied across the diodes which act as a synchronous detector. As the frequency modulated radio carrier moves above and below the resonant frequency, the phase shift varies above and below 90°. The detector converts this phase shift into an audio frequency signal which matches the original audio source.

Initially, I planned to build a copy of this receiver, but after doing a bit of research, I concluded that a helical resonator would be more practical at these frequencies. My new plan was to duplicate this circuit, except that I would substitute a helical resonator for the coaxial resonator.

The first step then was to design a helical resonator with an unloaded Q of 2000 at a resonant frequency of 110 MHz, the top of the FM band. Using

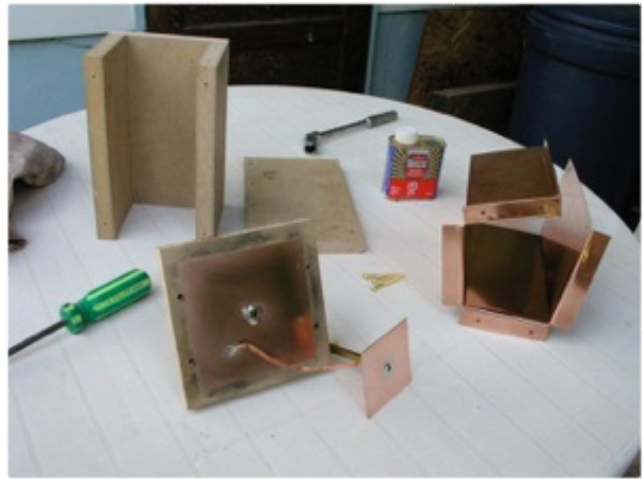


standard helical resonator design formula, the resulting resonator has an inner coil constructed from 4.3 turns of 9.5mm (3/8") copper tubing. Coil outside diameter is 65mm (2.6"), and coil length is 84mm (3.3").

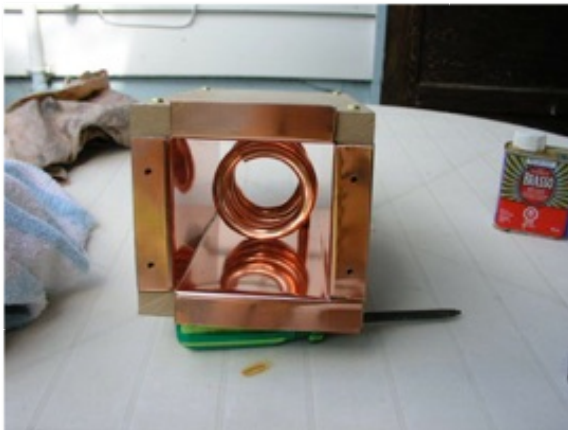
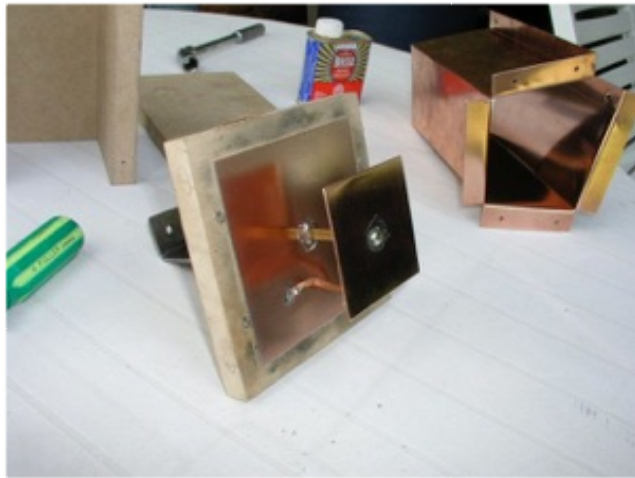
The shield is constructed from copper sheet, and is 84mm (3.3") square by 200mm (8") long. It is housed inside a wood enclosure

for rigidity. The shield is about 2" longer than required to allow room for coupling loops at the bottom, and for a tuning assembly at the top. The photo to the right shows the shield parts prior to assembly. The tuning mechanism is a small plate attached to a length of brass tubing which runs through the end cap. The rod is moved in and out by means of a screw. This changes the fringing capacitance at the open end of the coil. The closer the plate is to the coil, the lower the resonant frequency. The next photo shows

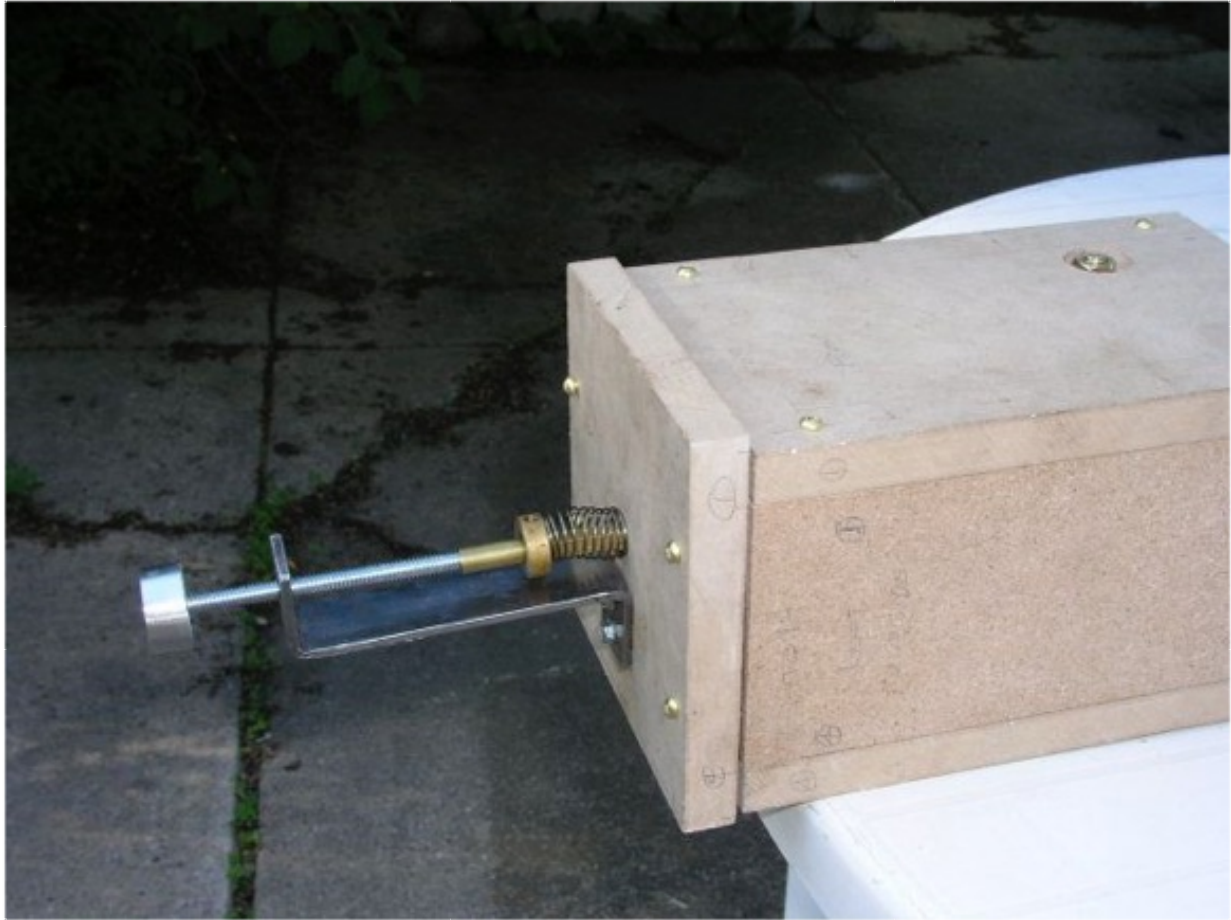
the top cap with tuning mechanism assembled. The tubing has a square cross section to prevent the assembly from turning. It slides inside a slightly larger piece of square tubing. This type of tubing is available at hobby shops and comes in a range of sizes suitable for close sliding fits. The coil and the inside of the shield were polished to remove



oxidization, and hence maximize Q. The partially assembled resonator is shown in the next two photos. The photo on the left is of the top end, and the photo on the right is of the bottom end.

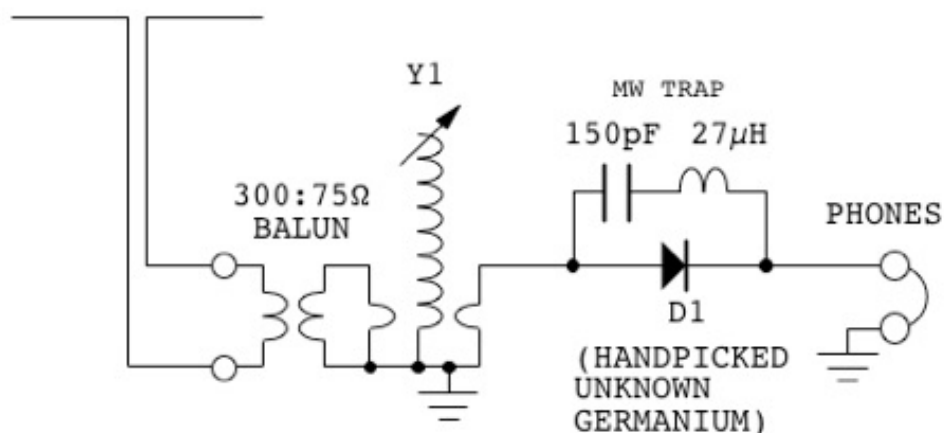


The next photo shows the top cap installed and the exterior part of the tuning mechanism:



I decided that for initial testing, it would be best to keep things simple and use a slope detector circuit. This is shown in the following schematic:

DIPOLE ANTENNA

**HELICAL RESONATOR Y1:**

COPPER TUBING 9.5mm (3/8")

4.3 TURNS

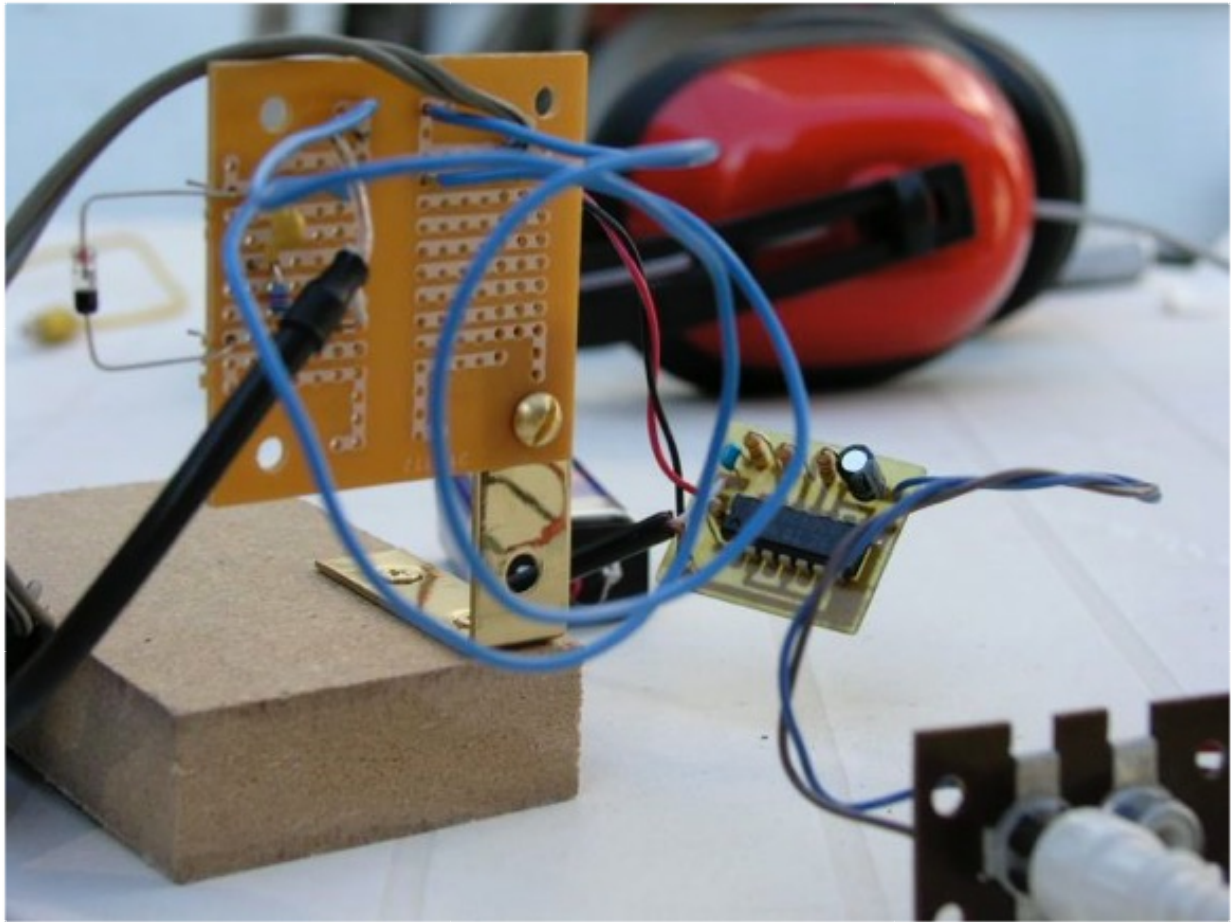
OUTSIDE DIAMETER 65mm

COIL LENGTH 84mm

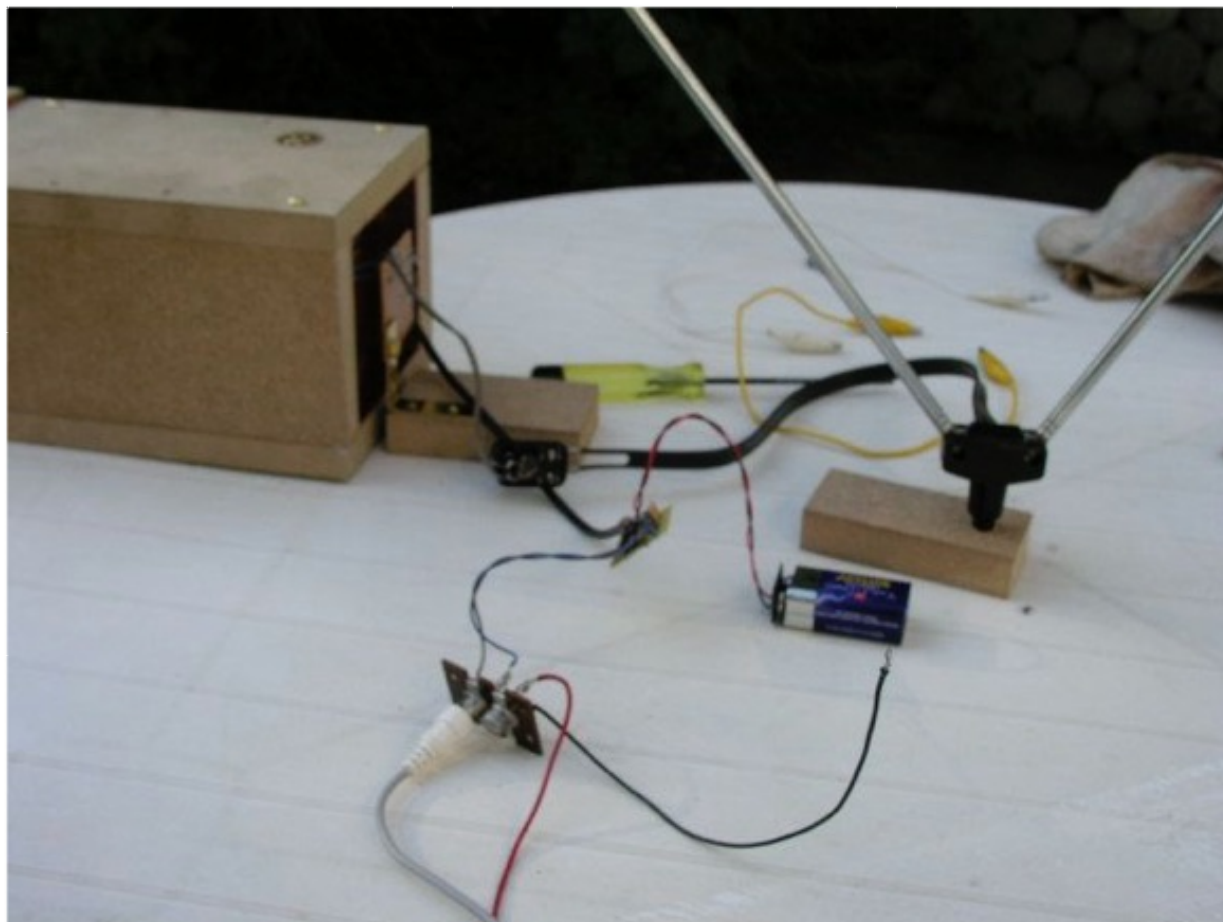
SHIELD SIZE 85mm SQUARE X 198mm HIGH

TUNING BY MEANS OF MOVABLE END PLATE IN TOP OF RESONATOR

The 27uH choke and 150pF cap are a low pass filter to trap out a local high powered AM station that was causing some interference problems. For a diode, I used a 1N34A initially, but found another unknown type in my parts box which worked slightly better. It may in fact also be a 1N34A from a different manufacturer. The detector and coupling loops were built on a small circuit board and mounted on a block of wood so that the assembly could be repositioned easily to obtain the best performance. The assembly is shown below.



The RF and detector coupling loops are blue hook-up wire. The little postage stamp sized circuit board is a low power headphone amplifier which was used in conjunction with my relatively insensitive headphones to make testing a bit more painless. The initial working set-up is shown below:



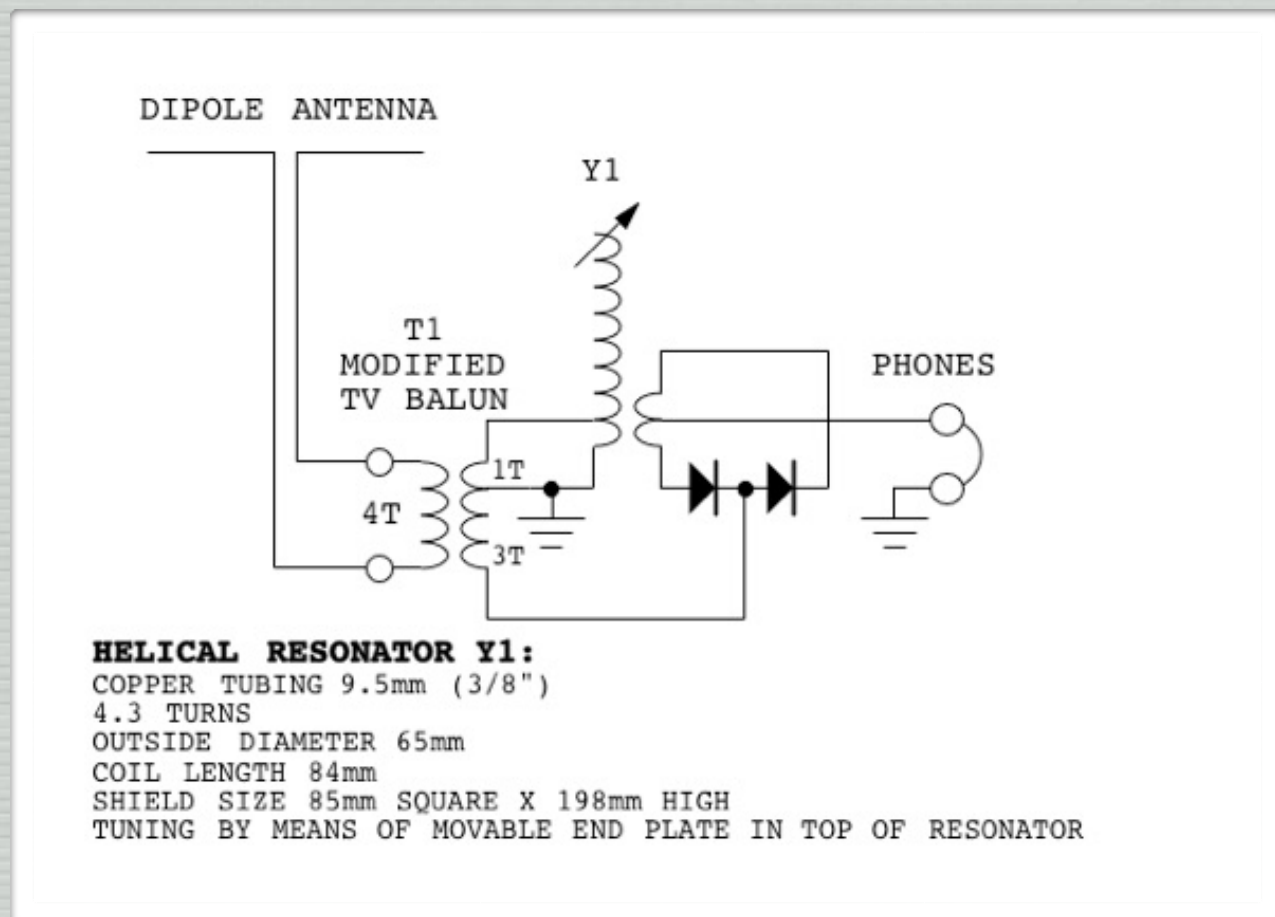
Reception was fairly good. The signal was weak using my piezo phones without any amplification. So, I connected in the headphone amplifier, and did all the remaining testing with it. Selectivity was very good. However, I don't have any easy means to measure the Q . I found that I could easily pick either side of a station's centre frequency for detection, and if I tuned dead centre, the signal became very distorted. That leads me to believe that the Q is very high. I couldn't get that kind of precision with earlier experimental sets which used a coil/capacitor tuned circuit.

So with that bit of success, I started thinking about making a true discriminator. As mentioned above, I had intended to duplicate Ed Richley's circuit except that the coaxial resonator would be replaced with the helical one. However, after reviewing the original circuit, I concluded that two of the transformers could be eliminated. The first transformer is a balun to convert from an unbalanced RF signal from the antenna to a balanced one. Since I intended to use a dipole antenna, this was unnecessary.

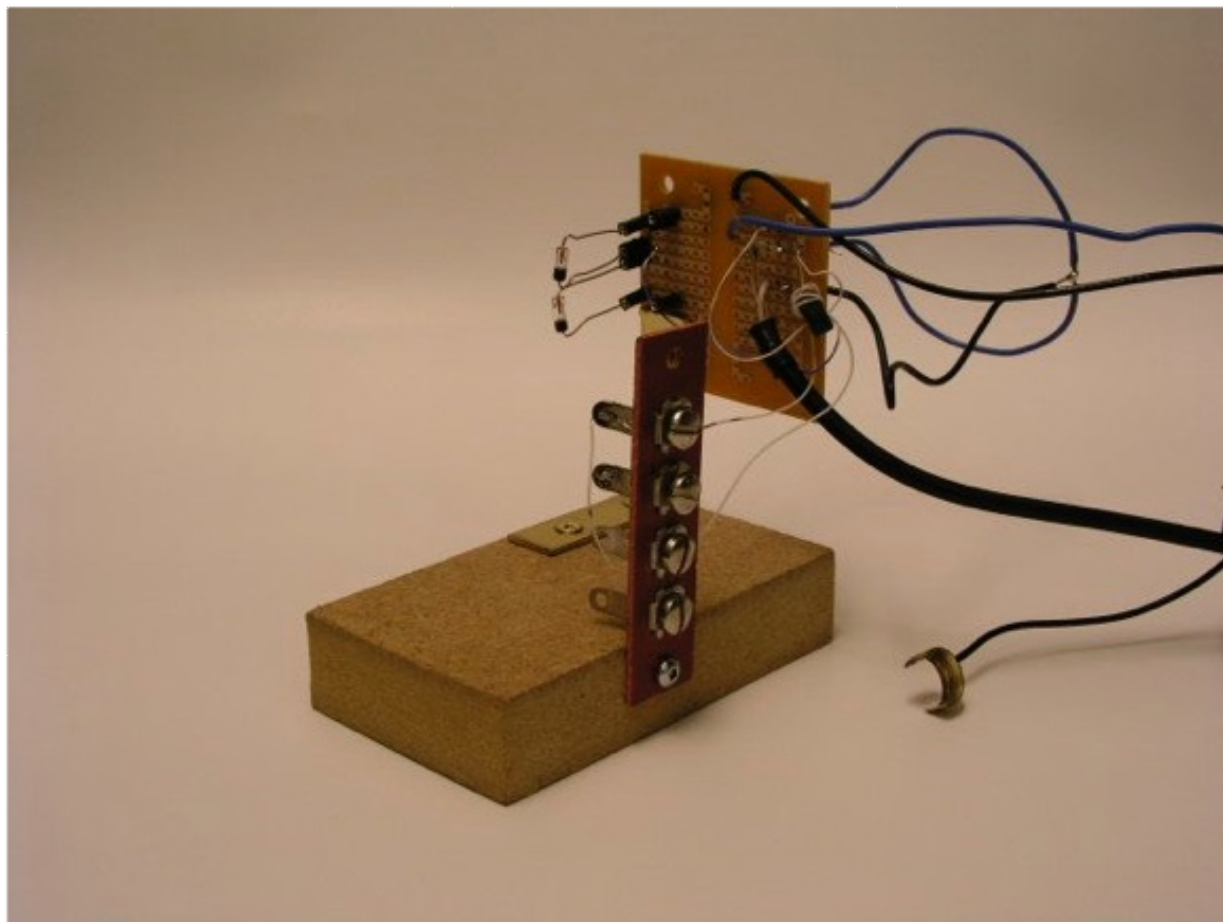
Rather than excite the resonator via coupling loops through the small capacitors, I decided to drive the resonator directly at a tap near the ground

end of the resonator coil. This eliminated the need for the balanced secondary winding on T3.

I decided that I could combine T2 and T3 into a single transformer. I had disassembled several baluns and found some to have two-hole cores and some were simple toroids. I used the toroid from one of these and wound a 4-turn primary, and 4-turn secondary. The secondary has a tap after the first turn which is grounded. The schematic follows:



The secondary arrangement still gives the same 3:1 power ratio between the diodes and the resonator excitation, but the circuit is much simpler. The revised coupler/detector board is shown below:



The black wire with the brass clip is for connecting to a tap on the resonator coil. I made it this way so that I could quickly try different positions. Optimum turns out to be about 40mm (1.5") from ground.

The pickup loop is the single loop of blue wire with the audio output tap at the halfway position (black wire).

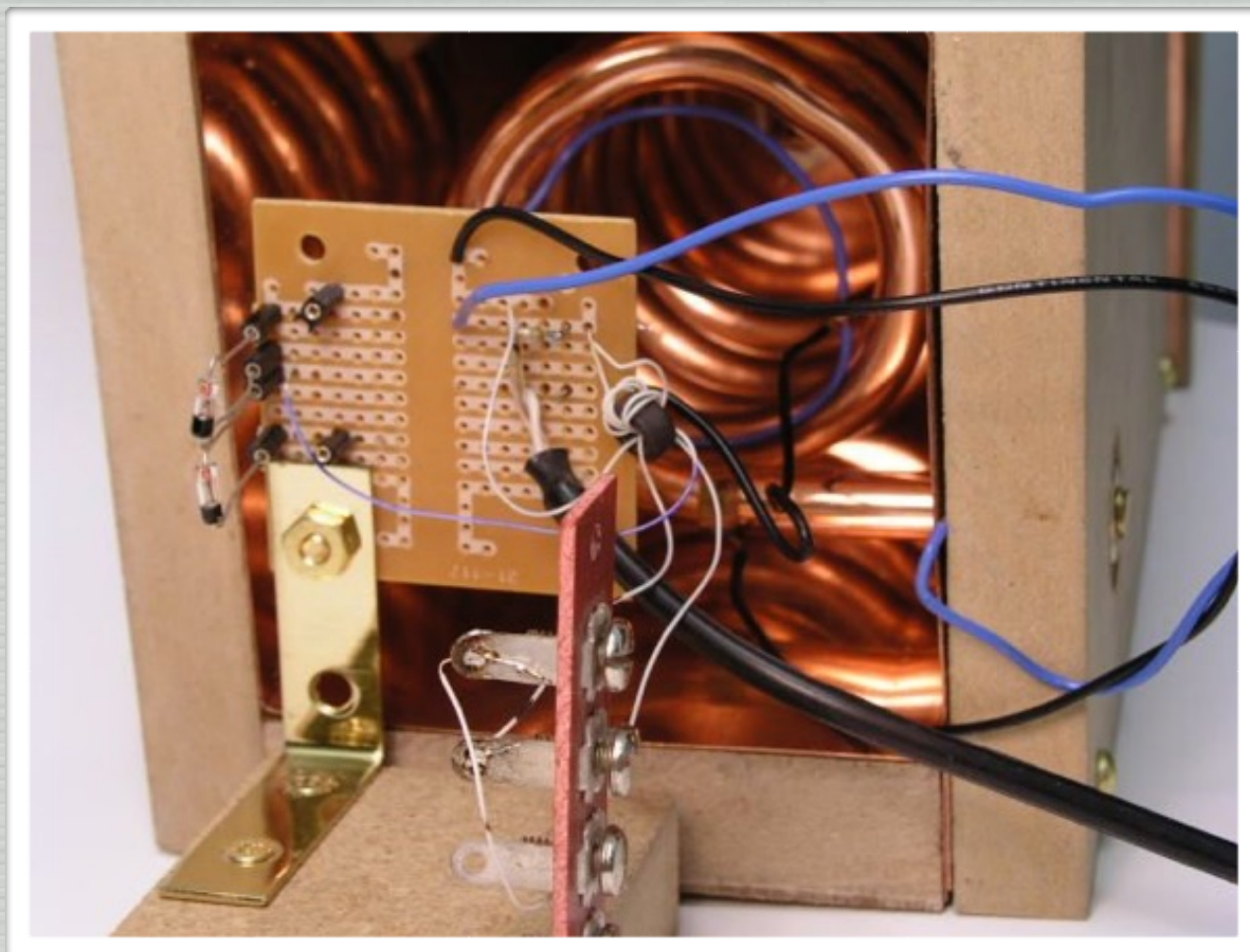
Diodes are socket mounted so that different ones may be tried without fuss. I didn't put in an AM trap this time, because the circuit arrangement is not conducive to AM pickup, since the diodes are essentially shorted at MW frequencies by the pickup loop.

Here's a brief description of how the circuit works:

Input transformer T1 splits the incoming RF (untuned) into two signals 180 degrees out of phase with reference to ground. The low level side goes to the resonator and the high level side goes to the common point of the diodes. The voltage induced by the resonator into the pickup loop will be 90 degrees out of phase with the the input signal. This is the nature of a loosely

coupled tuned circuit at resonance. The phase of the signal on the pickup coil will vary on either side of 90 degrees as the carrier is frequency modulated. The "90 degree" signal is applied to the outside ends of the diodes while the 180 degree signal is applied to the diode common point which then act as a quadrature detector. Hence it is essentially the same mode of operation as Richley's original circuit.

The following photo shows the discriminator assembly in position:



Now, with everything connected up, and after finding the best position for the pickup coil I found that the discriminator appears to be working correctly. Tuning is sharper, and there are no double slopes to select as I could previously. In fact tuning this receiver has very much the same feel as tuning a commercially made FM receiver. Audio level has increased significantly too. This is something I had been wondering about. I was concerned that a true discriminator might be less sensitive than a slope detector, but it appears not to be the case.

2010-11-28 Update:

Since the original material first appeared on this page, I've continued to tinker with this circuit, resulting in several incremental improvements. Although the improvements came in many small increments, the cumulative result is that this is now a very good performing receiver. Improvements listed in order of importance (most important first) are:

- Changing the detector diodes to Avago HSMS-2850;
- Changing the turns ratio on the RF input transformer;
- Getting a good set of sound powered headphones;
- Permanently mounting the detector loop;
- Finding a good antenna location;
- Shortening the resonator helix.

Diodes

The Avago (formerly Agilent) HSMS-2850 diodes are rather odd ones. I had purchased these along with a number of other different types of detector diodes, more or less at random, to test their effectiveness. These particular diodes were described as "**zero bias**" which made them too intriguing to pass up. When they arrived, I set them aside and didn't think about them again until I ran across [this page on Dick Kleijer's site](#). He had also built an FM crystal set and had tested a number of different diodes. Among them were the HSMS-2850's which turned out to be his best performers. I dug through my diode assortment and confirmed that they were the same ones I had. These are surface mount, and so I had to construct a small printed circuit adapter board. Otherwise, I would have tried them much sooner. When I tried them, there was a considerable improvement in performance. I mentioned that these diodes are odd ones. They have a very low R_0 (zero crossing resistance) of about 5000 ohms (many thanks to Mike Tuggle who measured them for me). Coincidentally, this is about the same R_0 as a galena detector. The low R_0 would normally make them a bad choice as a crystal set detector (galena aficionados notwithstanding). However, it appears that this particular resonator circuit has a very low resonant RF output resistance, which turns out to be a good match to the diodes. For more info on this, see [Article #4 on Ben Tongue's site](#). This low RF resistance has another

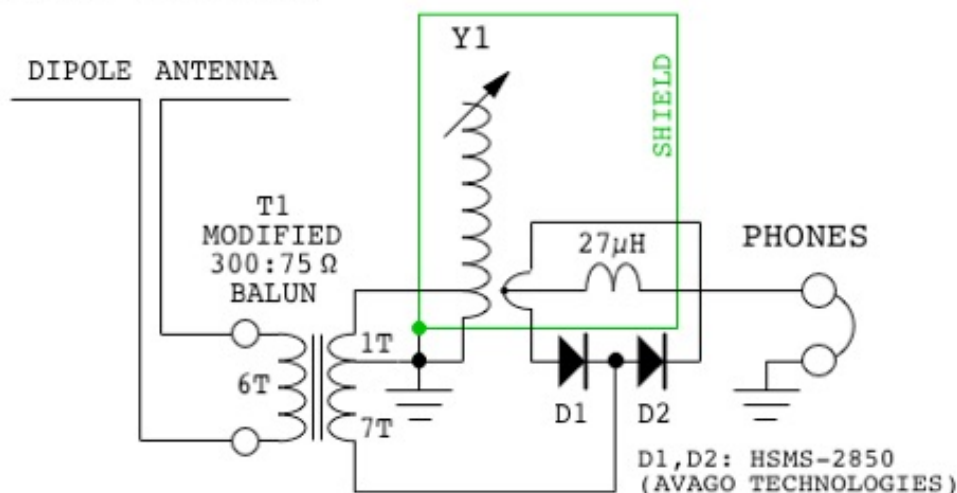
consequence which is discussed below.

In addition to the above mentioned diodes, I also recently tested Sanyo 1SS351 diodes. These are a surface mount type, with two diodes in a single package, and while not quite as sensitive as the HSMS-2850's they are significantly better than any of the germaniums or other Schottkys that I've tested. I also tried paralleling two of these, and got a further improvement in performance. In a listening test (which was completely subjective) I found it difficult to tell much difference between the parallel 1SS351's and the single HSMS-2850's.

RF Input Transformer

Getting the best turns ratio for the RF input transformer was an iterative procedure which also affected the optimum input tap position on the resonator. The schematic appearing earlier on this page shows a primary with 4 turns, and a secondary with 4 turns, with a grounded tap at 1 turn. After much experimentation (and wire breakage), I currently have a primary with 6 turns, and a secondary with 8 turns, with the grounded tap again at 1 turn. This is the current schematic:

FM CRYSTAL SET R. WEAVER REVISED 2010-11-06



HELICAL RESONATOR Y1:
COPPER TUBING 9.5mm (3/8")
3.75 TURNS
OUTSIDE DIAMETER 65mm
COIL LENGTH 84 mm
SHIELD SIZE 84 mm SQUARE X 200mm HIGH
TUNING BY MEANS OF MOVABLE END PLATE IN TOP OF RESONATOR

I might have arrived at this turns ratio a bit sooner if I hadn't made a bit of a blunder, confusing a dipole antenna with a folded dipole antenna, and thinking my antenna impedance was 300 ohms when in fact it is 75 ohms. (You may pick up on this goof in the earlier text of this page, which I haven't corrected yet.) I'm not yet at the point where I will claim this transformer configuration to be optimum, but it is much improved over what I had before.

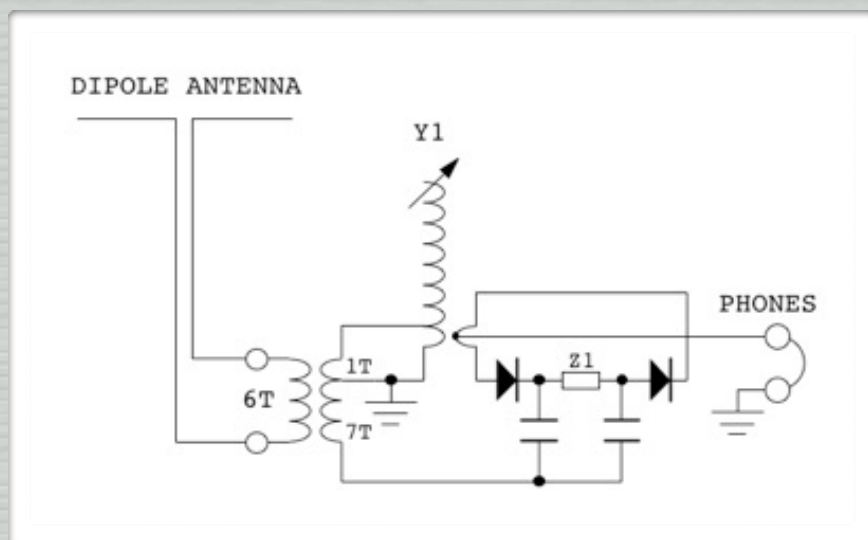
Another addition is the $27\mu\text{H}$ choke connected between the centre tap on the detector loop and the phones. This seems to help isolate the audio wiring from the RF part the circuit, and vice versa. This improvement is subjective at this point (it seems to increase volume), but regardless, it doesn't appear to be a bad idea.

There were a few other changes made to the circuit as well, but in the end, except for the diodes, the revised RF transformer windings, and the addition of the $27\mu\text{H}$ choke, the other changes resulted in negligible improvements. Hence, they were dropped.

While on the subject of the schematic diagram, alert readers will note the apparent short circuit at audio frequencies if the diodes happen to be conducting. The consequence of this is that when receiving a very strong signal, there is an upper limit to how much audio the detector will produce. My earlier circuit simulation verified this, but I haven't yet encountered a real life signal strong enough to hit this limit. However, I have allowed for

circuit modifications should this ever become a problem. It would involve the addition of a resistive or reactive component (Z1) between the diodes as shown in the diagram here. The circuit model used in the simulation does

not yet have sufficiently accurate parameters for the diodes or other components, to give a good idea what values to use for Z1 or the coupling capacitors. My circuit board has several strategically located



jumper plugs to allow for this future addition without the need for any soldering or de-soldering.

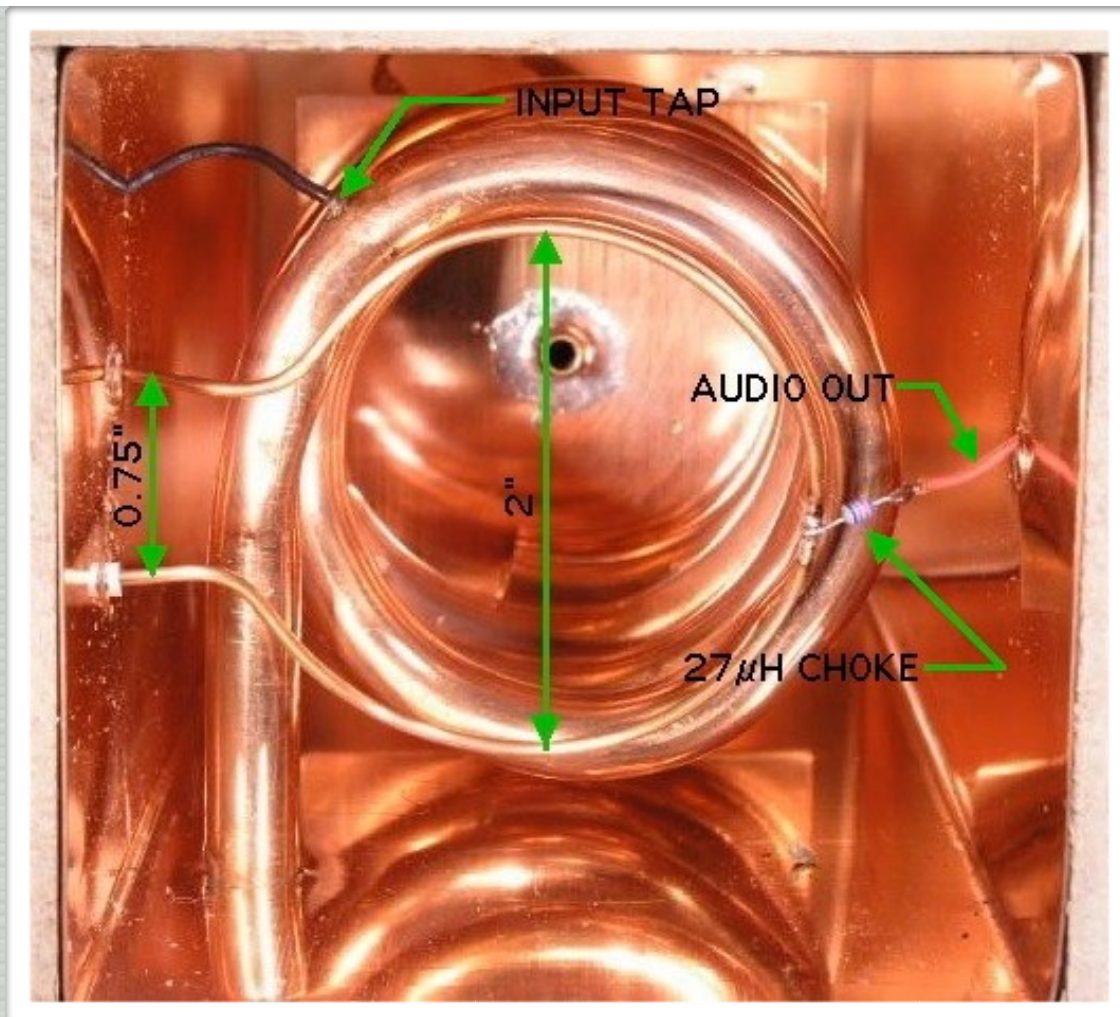
Sound Powered Phones

There's not much I can say about sound powered phones other than: If you're serious about crystal radios, eventually you'll have to get a pair. There is nothing else that compares in sensitivity. Piezo phones are not bad if you have nothing else available, but simply don't compare to sound powered phones. I was lucky enough to get a pair of Western Electric SP phones (thanks to Darryl Boyd), and with the other improvements that were made in the receiver, there is no longer any need for an amplifier, not even for testing purposes.

The Western Electric phones (model D173014) have an impedance of about 600 ohms per element, and I have them wired in series for a total impedance of 1200 ohms. This turns out to be such a good match for the low impedance detector, that I have not found any advantage to using an audio matching transformer. Originally, I tested these with a Bogen T725 transformer wired as an autotransformer. The best transformer configurations were the 2:1 and 4:1 ratios. However, I couldn't honestly detect any improvement over the direct connection using no transformer at all. I did notice a slight difference in frequency response (better bass with the transformer), but no net improvement in volume using the transformer. I'm guessing that the optimum impedance would be somewhere around 2400 to 3000 ohms, but the transformer's insertion loss probably negated any benefits from the better impedance match.

Detector Loop Mounting

Originally, as shown in the early photos above, I mounted the diodes and detector loop on a separate moveable base. Once I'd determined the optimum position for the loop, I mounted it permanently through the side of the enclosure. This eliminated quite a bit of excess wire which is never good to have when dealing with VHF. The RF transformer and diodes are now mounted on the side of the enclosure where the leads come through. Here is a detail of how the detector mounts:



The detector loop is 50 mm (2") diameter #14 AWG (1.6 mm) copper wire, which is stiff enough to maintain optimum shape and position, once those have been determined. It is a friction fit through the side of the enclosure. Both leads are insulated where they pass through the shield.

The detector loop could mount through any of the four sides of the shield. However I chose the arrangement shown here, where both ends of the loop cross the ground end of the helix at 90°. It's my belief that this would minimize any possible unbalance in the loop due to ground capacitance effects.

What isn't shown in the photo, is the separation between the detector loop and the bottom of resonator helix. The distance is approximately 16 mm (5/8"). The loop has a bit of a twist in it, to follow the pitch of the helix, so that separation is a fairly constant 16 mm at all points, except where it bends around the ground end of the helix. Audio is taken off at the middle of the loop through the 27 μ H choke. The input tap (black wire) is connected to the resonator helix about 75 mm (3")

from the grounded end.

Antenna Location

Unfortunately, antenna location is much more critical when dealing with VHF than when dealing with medium wave. A change in position of less than a metre can drastically affect reception. Initially, I found that to receive some stations, the antenna would have to be in one position, and to receive other stations, the antenna would have to be moved somewhere else. In all cases the antenna would have to be rotated to get the strongest signal.

My antenna is a simple set of rabbit ears (dipole) that was supplied with some long forgotten television receiver. I have it mounted on a camera tripod with a pan head, making it easy to rotate.

Currently, it sits in one corner of my house where I find that it gives good reception for all of my local FM stations (except one; more on that below). I have no explanation for why this particular location is best. No doubt, there are many complicated factors. However, I do note that this is in a far corner of my house which likely has the least amount of electrical wiring in the walls and ceiling.

Resonator Helix Length

Originally the helix was 4.3 turns of tubing. According to my design calculations this should have given a resonant frequency of about 110 MHz, just above the top of the FM band. In practice, it gave a resonant frequency of just a bit over 103 MHz. I expect this is mainly because I wasn't able to make the helix diameter exactly as designed.

The resonant frequency is also affected by fringing capacitance between the ungrounded end of the helix and the outer shield. If the helix is not perfectly centred in the shield (particularly the ungrounded end) the fringing capacitance will be higher and the resonant frequency will be lower. The resonant frequency can often be increased slightly by adjusting the position of the helix (ie., making sure it's exactly centred). However I wasn't able to increase the resonance enough, using this method. So, I trimmed pieces off the end of the helix until the resonance increased to an acceptable value.

After trimming, the helix was stretched out lengthwise to return the

overall length to the design value of 84mm (3.3").

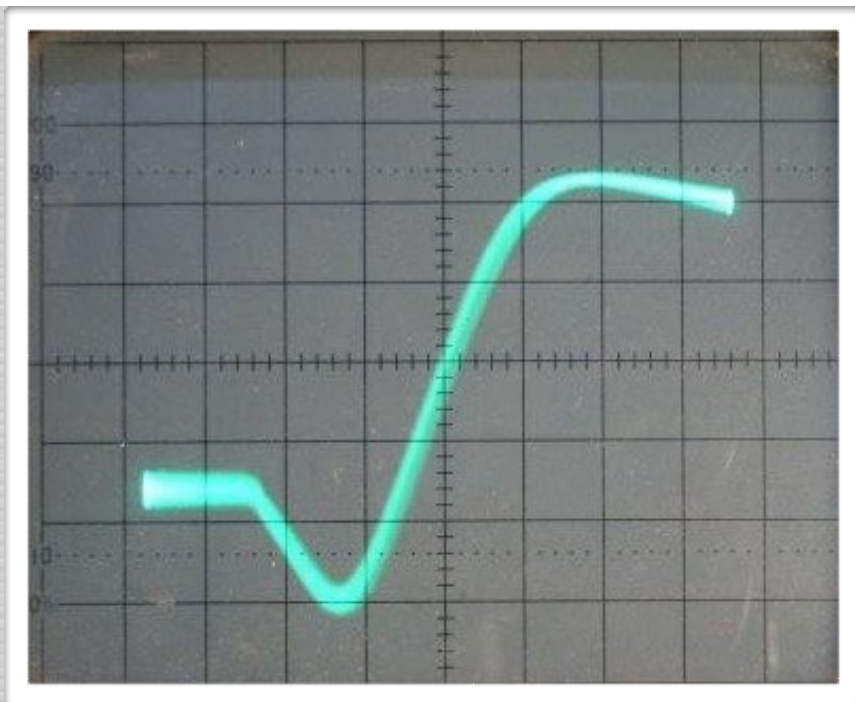
Currently, the the helix is 3.75 turns, and it tunes up to 106.3 MHz which covers all of the FM stations in my area, but not quite the whole FM band.

Performance

Shortly after building the phase discriminator version of the detector circuit, I was asked—quite legitimately—whether I was certain that the circuit was behaving as a proper phase detector, and not just an oddly configured slope detector. So, it was quite important that I verify its operation. Previously, I'd run a circuit simulation which indicated it would work. Then subsequently, I put a digital voltmeter on the audio output and verified that as an unmodulated carrier was slowly and manually swept across the resonant frequency of the receiver, the output went negative, crossed through zero, became positive and then dropped to zero again. But that's a far cry from actually seeing a decent response curve on a scope.

Unfortunately, I don't have a VHF signal generator which can be suitably frequency modulated. However, I do have a cheap FM modulator (intended for playing portable music players through a car's FM radio). It uses a Rohm BA1404 FM modulator IC. The RF output is tied back into the 12V power cable which plugs into the car's cigar lighter. This was not suitable for providing a reliable and consistent signal to the receiver. So, I had to perform some surgery. Thanks to an online data sheet for the BA1404, I was able to locate the RF output (pin 7, for anyone interested), and connect a separate RF output lead.

Once I managed to separate the RF output, I got a nice clean signal. My audio sweep source is a sine wave from an audio generator. The only remaining complication was that the FM modulation was slightly out of phase relative to the input audio signal. So, I had to build an adjustable phase shift circuit to go between the audio generator and the scope X-input. Once it was adjusted properly, the waveform cleaned up very nicely, and I was quite thrilled to see a fairly good S-shaped discriminator response curve which is shown here:

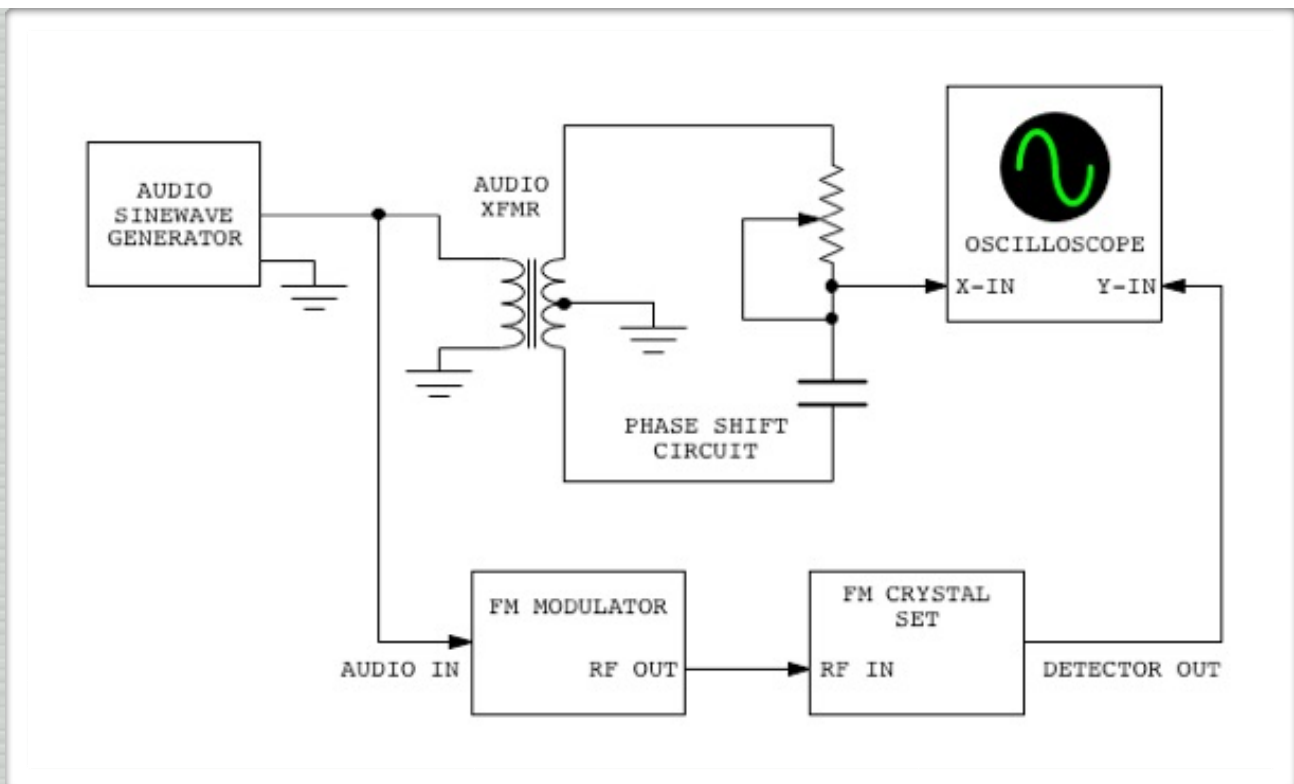


This is the actual DC response of the detector with an input FM signal of about 100 MHz. Mid position on the graticule is 0 Volts DC. Some asymmetry can be seen in the response curve; the skirt on the right tapers off much more gradually than that on the left. At some point I will probably investigate why this is happening, though I'm not too concerned about it. The flat section on the left is an artifact of the FM modulator. All things considered, I'm quite happy with the results.

Unfortunately, because the modulator is uncalibrated, I'm unable to say just what the actual bandwidth is. I hope to address this in the future.

As a side note, it can be seen that the trace is somewhat fuzzy. This is because there is a superimposed 19 kHz stereo pilot tone which is produced by the FM modulator. This had me baffled for a while until it dawned on me what it was. By adjusting the audio generator frequency, the 19 kHz signal can be made almost stationary, but still moves too fast for the camera to catch it.

The test set-up, used to generate the above response curve, is shown here:



Listening Test

I have twelve local FM stations (within approx. 30 km). With this receiver I can clearly hear all except for two of them. Of those two, the first (91.7 MHz) seems to be temporarily off the air (although I can pick up its unmodulated carrier on other receivers). The second (100.3 MHz) is so weak that I can barely pick it up on a regular FM receiver, and even then, it is buried in noise and is barely intelligible.

So, I wasn't too upset about not picking it up on the crystal set.

The ten local FM stations, which I can hear clearly, range in power from 1300 Watts to 100,000 Watts. All of them can be heard at pleasant volume in a reasonably quiet room. The 1300 Watt station is one of the loudest. However, its transmitter is probably closer to my listening location than the others. The receiver is selective enough that there is absolutely no overlap in stations. Audio quality is very good with the sound powered phones.

Four of the stations are strong enough that they can be heard fairly well with Sony MDR-W08 Sport Walkman phones when properly matched with a Bogen T725 transformer. Although the volume was considerably lower than with the sound powered phones, it was still quite intelligible.

[Here is an audio clip](http://electronbunker.ca/eb/FMCrystalSet.html) tuning through the ten local stations starting at

88.7 MHz and ending at 105.5 MHz, which gives a general idea of the audio quality. File size is 1.6 MB. It was created by connecting the crystal set audio output through a simple RC de-emphasis filter, into a microphone preamp and then into the audio input of my computer running Audacity 1.25 software. The audio is exactly as recorded with no editing or other processing. You will notice that the sound quality changes rather erratically during tuning. This is due to backlash in the tuning mechanism (particularly troublesome at the bottom of the band), and simultaneous adjustment of antenna direction.

More to Come

While this project is close to being complete, a few things remain to be done.

Firstly, the tuning mechanism is very non linear. Tuning at the low end of the band is very touchy, and backlash in the adjusting screw makes tuning these stations a bit frustrating. I'm currently looking at an alternative tuning method which should result in more linear tuning.

Secondly, I would like to test the receiver with a good quality outdoor FM antenna.

Finally, I need to do some final clean-up of the construction and make